



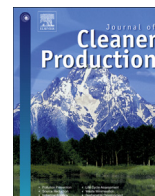
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Environmental and resource aspects of substituting cemented carbide with polycrystalline diamond: The case of machining tools

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ABSTRACT

Synthetic diamond competes with the conventional cemented carbide (WC–Co) tool material in some applications due to its extreme hardness. However, so far, these materials have not been compared from a life cycle perspective regarding their environmental and resource impacts. The aims of this study are i) to provide detailed life cycle assessment (LCA) results for industrial polycrystalline diamond (PCD) production from diamond grit produced via high-pressure high-temperature (HPHT) synthesis and ii) to conduct the first comparative LCA of PCD and WC–Co tools for the cases of wood working and titanium alloys machining. The results show that the main hotspot in HPHT synthesis of diamond grit, which is the main precursor to PCD, is the use of WC–Co in the high-pressure apparatus. In PCD tool production, the electricity input and the use of tungsten and molybdenum contribute the most to environmental and resource impacts. The environmental and resource impacts of the PCD tool production can be reduced with 53–83% if solar electricity and full WC–Co recycling is applied. The comparison shows high environmental and resource improvements when substituting WC–Co tools with PCD tools in wood working, but not in titanium alloys machining.

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1. Introduction

Diamond is a material well known for its exceptional hardness. Industrial diamond (excluding gemstones) is dominated (99%) by synthetically produced diamond, including grit, powder and stones (USGS, 2018a). Some influencing factors in establishing the dominant position of synthetic diamonds over natural diamonds in industrial applications are the possibility of quality control, customization of size, shape and mechanical properties (USGS, 2018a; Vohler et al., 2010) as well as the possibility to produce large quantities (USGS, 2018b). The conventional production of synthetic diamond is conducted via high-pressure high-temperature (HPHT) synthesis (Kasu, 2016; Palyanov et al., 2015), which recreates the conditions required for natural diamond formation (Kesler and Simon, 2015). Chemical vapor deposition synthesis, utilizing a carbon-containing gas as the diamond precursor

(Palyanov et al., 2015), and detonation nanodiamond synthesis, where nanodiamonds are produced from carbon-containing explosives (Shenderova and Nunn, 2017), are also conducted but to a lesser extent. Diamond is used in many industrial applications, ranging from cutting and grinding of wood, metals and rocks to optical windows and heat sinks (Kasu, 2016; Kesler and Simon, 2015; Konstanty, 2005; USGS, 2018b). By enabling faster cutting, more accurate and less costly operations, diamond tools have been adopted in industries such as wood working, stone cutting, metal cutting and machining of ceramics (Konstanty, 2005). Diamond tools, including polycrystalline diamond (PCD) tools, compete with conventional cutting tools such as cemented carbides in applications where high hardness is of utmost importance (Konstanty, 2014). PCD is commercially produced by the consolidation of synthetic diamond powder, i.e. crushed diamond grit typically produced via HPHT synthesis (Vohler et al., 2010), and cobalt powder (Konstanty, 2005). The production technology for PCD has not changed significantly since its invention (Jaworska et al., 2018). Furthermore, the trend for cutting tools is towards an increased use of superhard cutting materials, especially PCD, mainly due to changes in workpiece materials towards e.g. high-strength materials (Bobzin, 2017).

Abbreviations: CED, cumulative energy demand; HPHT, high-pressure high-temperature; LCA, life cycle assessment; LCI, life cycle inventory; LCIA, life cycle impact assessment; PCD, polycrystalline diamond; WC–Co, cemented carbide.

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Besides the advantageous properties of PCD and its importance as a tool material, there are also indications that PCD could be preferable from an environmental and resource perspective compared to the conventional hard tool material of cemented carbide (WC-Co). Tungsten, the main constituent of WC-Co, is a geochemically scarce material (available at 1 ppm in the Earth's crust) while carbon, the main constituent of PCD, is comparatively abundant (1990 ppm) (Wedepohl, 1995). Due to the supply risk and economic importance of tungsten, it has been categorized as a critical raw material for the European Union (EU) (European Commission, 2017). The use of tungsten is also largely dissipative, meaning that it is lost in such a way that recovery is technically or economically unfeasible; the global average dissipation rate is >60% (Zimmermann and Gößling-Reisemann, 2013), but it can be 100% for highly dissipative products, such as tire studs (Furberg et al., 2019a). In addition, cobalt is also a scarce (24 ppm) material (Wedepohl, 1995), a critical material (European Commission, 2017), has a relatively high dissipation rate globally (30–40%) (Zimmermann and Gößling-Reisemann, 2013), and is present as a constituent in both WC-Co and PCD. Furthermore, some studies indicate that diamond tools constitute a more environmentally sustainable alternative to conventional tool materials due to e.g. longer lifetime and improved machining properties (Aurich et al., 2013; Mendoza et al., 2014). However, these studies do not consider the whole product life cycle of the tools but focus only on their use phase, e.g. the cutting operations.

Life cycle assessment (LCA) is the most well-developed tool for assessing environmental and resource impacts of products (Ness et al., 2007). It can provide information on life-cycle impact “hot-spots”, meaning the largest contributors in terms of processes, inputs and outputs, as well as highlight trade-offs and problem-shifting between different impacts and different life-cycle stages (Baumann and Tillman, 2004; Hauschild et al., 2018). While LCA results are available for WC-Co production (Furberg et al., 2019b), such results for the production of PCD via HPHT synthesis have not yet been presented. LCA results have been presented for laboratory synthetic diamond film production via the hot filament chemical vapor deposition synthesis route (Wilfong et al., 2012). Ferreira et al. (2019) presented some life-cycle environmental data for a master alloy containing detonation nanodiamonds (although not for the production of nanodiamonds, specifically). However, it is diamond powder that is applied in industrial PCD production (Konstanty, 2005), not diamond films or nanodiamonds.

The aims of this study are: i) to provide detailed LCA results for industrial PCD production from diamond grit produced via HPHT synthesis and ii) to conduct a comparative LCA of the use of PCD and WC-Co tools in specific machining applications. To the knowledge of the authors, this is the first LCA of industrial PCD production, the first LCA of PCD's precursor synthetic diamond grit, and the first LCA comparing PCD and WC-Co tools. This study thus provides ready-to-use LCA results for industrial production of both PCD and HPHT-made synthetic diamond grit, which can be used in future LCAs involving synthetic diamond products. The machining applications considered are wood working and titanium alloys machining, which illustrate different scale of opportunity and thus represent different substitution prospects. The intended audience is synthetic diamond tool manufacturers, tool users and the manufacturing industry in general as well as LCA researchers.

2. Materials and methods

There are two types of LCA: attributional and consequential LCA (Finnveden et al., 2009). The former is used to assess environmental impacts associated with a product system while the latter is applied to assess environmental impacts of changes in the product system.

An LCA can cover the entire life cycle of a product or service, i.e. cradle-to-grave, or parts of the life cycle, such as from raw material extraction to production, i.e. cradle to gate (Baumann and Tillman, 2004). This study is an attributional cradle-to-grave comparative LCA case study of the use of PCD and WC-Co tools in wood working and titanium alloys machining. An attributional LCA was conducted to provide information on the environmental and resource impacts associated with the product life cycles of PCD and WC-Co tools. This was further done in order to make it easy for LCA practitioners to use the results in subsequent LCAs of PCD products, whereas a consequential LCA only would consider changes in the product system if a PCD tool is to be used instead of a WC-Co tool. For the part of the study comparing PCD and WC-Co tools for wood working and titanium alloys machining, data was provided by Andersin (2019) and Leahy (2019) who work for the Element Six Group, henceforth referred to as “the collaborators”, at several workshop meetings. In addition, this study contains an attributional cradle-to-gate LCA for the production of micron-sized diamond grit via HPHT synthesis. All the modelling was conducted in accordance with the ISO 14040 standard (ISO, 2006), using the OpenLCA software version 1.10.3 (GreenDelta, 2020), which was selected since it is an open access software commonly used by LCA practitioners.

2.1. Functional units

The functional unit in LCA provides a quantitative measure to which all environmental and resource impacts are related. For the cradle-to-gate assessment of synthetic diamond grit production via HPHT, the functional unit of 1 g diamond grit was applied (corresponding to 5 carat). In the comparison between PCD and WC-Co tools in wood working, the functional unit was the mass of wood removed by one WC-Co tool during its lifetime. In titanium alloys machining, WC-Co and PCD mainly compete in finishing applications, where the surface area generated by one WC-Co tool during its lifetime was selected as the functional unit in this case. The collaborators report that the amount of workpiece material removed in wood working and the surface area generated in titanium alloys machining is increased by approximately 100 and 10 times, respectively, when a PCD tool is applied compared to a WC-Co tool over the tools' lifetime. Consequently, in order to remove as much workpiece material as one WC-Co tool in wood working and to generate the same amount of surface area as one WC-Co tool in titanium alloys machining, 0.01 and 0.1 PCD tools are required in order to fulfill the same functional units for the two respective applications. The resulting workpiece surface quality was further reported by the collaborators to be similar in both application cases.

2.2. Systems studied

The systems studied include synthetic diamond grit production via HPHT and the comparison between PCD and WC-Co tools in wood working and titanium alloys machining, see Section 2.2.1 and 2.2.2. Allocation by cut off was applied for recycled materials throughout the system, implying that they are only responsible for direct impacts during recycling processes and not for any impacts further upstream (Ekvall and Tillman, 1997). This means that recycled materials are “cut off” after use, i.e. not followed anymore, whereas a share of recycled materials is introduced upstream (such as recycled WC-Co in this case), which thus reduces impacts of material production (Nordelöf et al., 2019).

2.2.1. Synthetic diamond grit production

The diamond grit production via HPHT synthesis is illustrated in Fig. 2 and described in more detail in Section 3.1. China dominates

the global synthetic diamond production by 92% (USGS, 2018a) and the world's largest industrial producer of synthetic diamond is situated in the Henan province (Han et al., 2011a). Thus, the synthetic diamond grit production was assumed to take place there.

2.2.2. Comparison between polycrystalline diamond and cemented carbide tools

Machining entails the removal of material from a workpiece and is one of the most important manufacturing processes (Prakash, 2014). In this case study, PCD and WC-Co tools were compared for fine-precision machining in wood working and for finishing of titanium alloys. These cases were selected together with the collaborators based on their area of expertise and their knowledge of PCD performance compared to WC-Co in different applications. Fine-precision machining in wood working here represents e.g. milling profiles of cabinets, furniture or kitchen units. The collaborators have substantial knowledge about PCD tool performance in wood working, both from own conducted tests and from their customers. Machining of titanium alloys is primarily conducted in the aerospace industry and currently WC-Co tools are mainly used for this purpose (Yang et al., 2014). The performance data for PCD tools in titanium alloys machining in this study does not reflect real use but is a conservative estimate by the collaborators.

The compared PCD and WC-Co tools each have four tips of PCD and WC-Co, respectively, on a tool body. In this study, generic tips and tools with a constitution commonly applied for these types of tools were assessed. In specific applications, however, the shape of the tips can vary since they are used to produce different geometries and dimensions of the workpiece. The shape of the tool body can also vary between different tool manufacturers, but it is often similar when used in the same applications. A schematic picture of a PCD and WC-Co tip, presenting the general tip dimensions applied in this study, is provided in Fig. 1.

The comparison between PCD and WC-Co tools is illustrated in Fig. 2 and described in more detail in Section 3. The WC-Co tips are produced and assumed to be used in Europe. The production of diamond powder by crushing and PCD tip production, including HPHT sintering, disc processing and electrical discharge machining, are located in Western Europe. The PCD tool was also assumed to be used within Europe. The assembly of the tool tips on the tool body was excluded from the comparison (see further Section 3.2.4).

2.3. Impact categories

Impact categories were selected in order to assess both environmental and resource impacts. The impact categories of climate change [kg CO₂ eq], terrestrial acidification [kg SO₂ eq] and freshwater eutrophication [kg P eq] from ReCiPe (version 1.1, hierarchist scenario, 2016) were selected to assess environmental impacts (Huijbregts et al., 2017). The indicators cumulative energy demand (CED) [MJ eq] (Frischknecht et al., 2015), mineral resource scarcity [kg Cu eq] from ReCiPe 2016 (Huijbregts et al., 2017) and abiotic

depletion [kg Sb eq] from CML-IA version 4.8 with reserve base (Guinée et al., 2002; van Oers, 2016; van Oers and Guinée, 2016) were selected to assess resource impacts. Note that both the mineral resource scarcity and abiotic depletion indicators aim to assess non-energetic, material resources, but do so from different perspectives. The mineral resource scarcity quantifies the additional cost of extracting additional minerals while the abiotic depletion quantifies how large an element's extraction is compared to its crustal abundance.

2.4. Background system data

In LCA, the system studied is often divided into a foreground system (Fig. 2), which is studied in detail, and a background system, where the latter contain e.g. the production of electricity and base chemicals and is modelled using more generic data. The *Ecoinvent database version 3.5 (2018)* was applied for the majority of the background system data in order to include e.g. generic information on transports, in the case of products, and transmission losses, in the case of electricity. A selection procedure was used in the *Ecoinvent database version 3.5 (2018)* where site-specific data (e.g. for inputs to HPHT production in China) was applied in firsthand when available, otherwise global data was used. If global data too was unavailable, then data representing "rest of the world, excluding Europe", was applied. When data was unavailable in the *Ecoinvent database version 3.5 (2018)*, other data sources, including peer-reviewed articles, were used. The background system data applied is presented in Section S3 in the Supplementary material (SM).

2.5. Uncertainty and break-even analysis

Uncertainty was assessed by the application of scenario and sensitivity analyses. Igos et al. (2019) suggest that such a basic uncertainty assessment can be applied when more detailed data on for example parameter probability distributions are missing, which was the case in this study.

In the scenario analysis, four scenarios were constructed by varying the type of electricity input to the foreground system and the recycling rate of WC-Co (Table 1). The scenarios were constructed to reflect impacts related to decisions within the power of the foreground system actors, e.g. diamond powder producers and tool makers. For example, a diamond powder producer can purchase certain types of electricity for use in their processes, while the type of electricity used in the background system is rather decided by their suppliers. Likewise, the tool maker can decide to use recycled WC-Co materials as inputs and to send discarded WC-Co to be recycled but have less influence over their suppliers' actions. The current scenario represents production as it is today, where the type of electricity in the foreground processes was chosen to comply with the situation in the respective location where the processes are taking place and the current WC-Co recycling rate of approximately 40% was applied (Shemi et al., 2018). Three corner-stone scenarios representing future possible improvements were also constructed: a solar scenario, a full recycling scenario and a solar-full recycling scenario. The solar scenario represents a case where the synthetic diamond producers use solar electricity in their processes. The full recycling scenario represents a 95% recycling rate of WC-Co, which is the yield of the zinc process typically used for WC-Co recycling (Shemi et al., 2018) and thus represent complete recycling via the zinc process. The solar-full recycling scenario represents the combination of both these two improvement scenarios.

In the sensitivity analysis, parameter values were changed one at a time in order to investigate variations in the LCA results relative

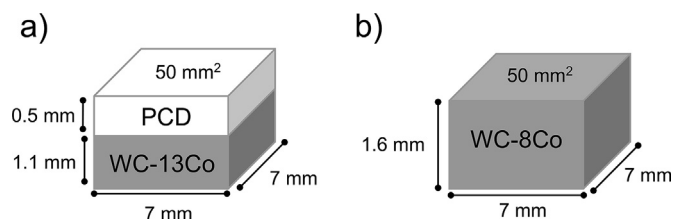


Fig. 1. Schematic picture of a) the polycrystalline diamond (PCD) tip and b) the cemented carbide (WC-Co) tip assessed in this study. WC-13Co = cemented carbide with 13 weight-% cobalt, WC-8Co = cemented carbide with 8 weight-% cobalt.

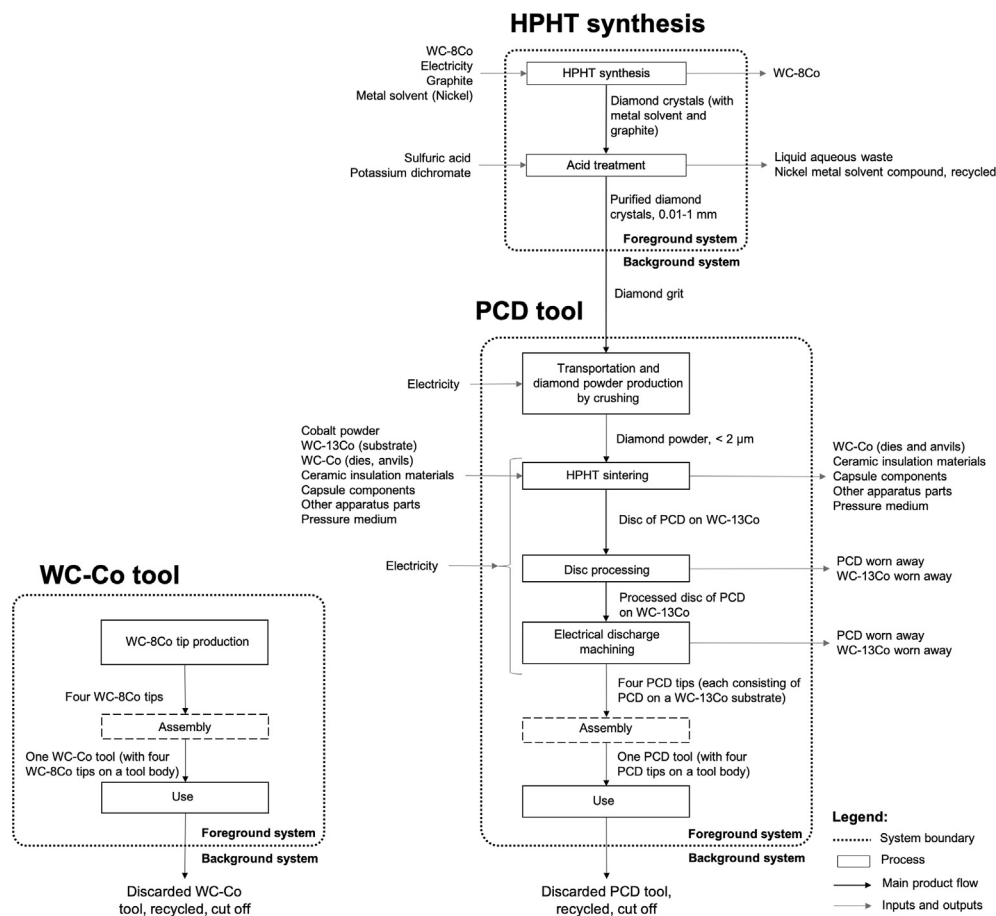


Fig. 2. Flowchart for the production of synthetic diamond grit via high-pressure high-temperature (HPHT) synthesis and for the life cycle of polycrystalline diamond (PCD) and cemented carbide (WC-Co) tools. The process of assembling the tool tips on the tool body, marked with dashed lines, is excluded from the comparison. The use processes either represent wood working or titanium alloys machining. For a more detailed flowchart of WC-Co production, see Furberg et al. (2019b). WC-8Co = cemented carbide with 8 weight-% cobalt and WC-13Co = cemented carbide with 13 weight-% cobalt.

Table 1
Scenarios for assessing model uncertainties. WC-Co = cemented carbide with various cobalt content.

	Current scenario	Solar scenario	Full recycling scenario	Solar-full recycling scenario
Type of direct electricity inputs to the foreground processes	Location-specific	Solar electricity	Location-specific	Solar electricity
Recycling rate of WC-Co [weight-%]	40	40	95	95

when baseline values were applied in the current scenario. In line with Igos et al. (2019), realistic ranges were applied for the sensitivity analysis when available. Otherwise, the parameter values were changed by $\pm 50\%$ of its baseline value to identify the parameters that requires specific attention in further investigations. A sensitivity analysis was conducted for the HPHT synthesis, which LCI data was based on information identified in various literature sources, and all the values applied for the sensitivity analysis of HPHT synthesis are provided in Table S1 in the SM. A sensitivity analysis was also conducted for industrial PCD production, for which the majority of the LCI data were provided directly from the collaborators. The LCI data provided by the collaborators on industrial PCD production were changed by $\pm 50\%$ of its baseline value in a similar manner as for the sensitivity analysis of HPHT synthesis to identify parameters of specific interest. Note that additional changes were made in the LCI data for industrial PCD production when this was needed for consistency, e.g. to fulfill mass balances. For a sensitivity analysis related to WC-Co production, please refer to Furberg et al. (2019b).

In addition to the scenario and sensitivity analysis, break-even points in the comparison between PCD and WC-Co tools were investigated, meaning that the performance difference between PCD and WC-Co tools at which their environmental and resource impacts are equal was quantified. The provided performance of PCD tools in wood working and titanium alloys machining (100- and 10-times improvement versus WC-Co, respectively) by the collaborators (Section 2.1), or other such performance estimates, can be compared to these numbers.

3. Calculations

This section describes the data sources and calculations of the LCA. Further details are provided in Section S1-S3 in the SM. Whenever parameter ranges were available, midpoint values were applied for the calculations, unless typical values other than the midpoint value within this range were indicated.

3.1. Synthetic diamond grit production

In HPHT synthesis, the carbon source graphite is dissolved in a metal solvent and then transformed into diamond powder by crystallization at typical pressures and temperatures of >5.5 GPa and 1300–1400°C, respectively (Kasu, 2016; Vohler et al., 2010). The metal solvent (sometimes called catalyst) reduces the requirements on temperatures and pressures to controllable levels (Marinescu et al., 2016) and nickel is typically applied as the solvent (Vohler et al., 2010). The mixture-weight of graphite and metal solvents was set to 1:1 based on Han et al. (2015), producing diamonds with the conventional cubic high-pressure apparatus assembly. The graphite-to-diamond conversion was assumed to be 50 weight-% based on that the typical amounts of diamond and non-reacted graphite in the process output are approximately equally large (Skury et al., 2004). The size, mechanical properties and shape of the produced synthetic diamond depend on a number of process parameters (Vohler et al., 2010). These include the temperature, pressure, form and nature of the applied graphite, the metal solvent applied and the synthesis time. Diamond crystals ranging from 0.1 to 1 mm in size can be industrially produced via HPHT synthesis (Kasu, 2016; Varnin et al., 2006). Large-volume cubic presses are commonly applied for synthetic diamond production in China (Li et al., 2020), having a power of 3.4–3.8 kW (Li et al., 2018; Zhang et al., 2015). Most studies report that for sizes of about 0.1–1 mm, reaction times range from a few to tens of minutes (Prikhna, 2008; Zhou et al., 2008). Based on this, a reaction time of 10 min was assumed, while the range of 2–30 min was tested in the sensitivity analysis.

The desired pressure in the reaction chamber is obtained by six WC-Co anvils, with a cobalt content of 8 weight-% (WC-8Co) (Han et al., 2011a). The weight of a conventional cubic apparatus WC-Co anvil is 4.25 kg (Han et al., 2011b) and the typical sample size in the apparatus is 27.22 cm³ (Han et al., 2015), which correspond to an output of about 14 g per cycle based on linear extrapolation of data on the general yield of industrial large volume apparatus provided by Prikhna (2008). The WC-Co anvils applied in industrial production are highly prone to material fatigue as a result of carrying alternating high-temperature and high-pressure loads (Chen et al., 2018; Yan et al., 2015), giving a lifetime of about 100 cycles (Prikhna, 2008), after which the anvils need to be replaced. Based on the weight of six anvils, the yield per cycle and the lifetime of the anvils, the resulting consumption of WC-Co per gram of diamond grit output from the HPHT synthesis is about 19 g.

After the process of HPHT synthesis, the synthesized diamond grit is separated from the nickel metal solvent, as well as the unreacted graphite, via the addition of acids (Skury et al., 2004). Still, up to 10 weight-% metal solvent can be included in the purified synthetic diamond output from this process (Marinescu et al., 2016) and 5% was assumed in this study, while the range from 0 to 10% was tested in the sensitivity analysis. Acids are typically recovered to a large extent in the diamond purification process, however, about 0.29 kg sulfuric acid and 0.04 kg potassium dichromate are consumed per kg produced synthetic diamond based on global data (Skury et al., 2004) and these acids become liquid waste. The nickel metal solvent was assumed to be recycled since industrial waste nickel catalysts can in general be recovered to a high degree, approaching a 100% recovery rate for many methods (Coman et al., 2013). The lowest recovery rate for waste nickel catalysts presented by Coman et al. (2013) at 85% was tested in the sensitivity analysis. Since diamond is chemically inert to most acids (Abbaschian et al., 2005), the yield of purified diamond crystals, i.e. diamond grit, in the acid treatment process was assumed to be 100%. The electricity used in purification was assumed to be negligible.

3.2. Comparison between PCD and WC-Co tools

3.2.1. Transportation and diamond powder production by crushing

The diamond grit was assumed to be transported from the production site, located in China, to Europe via freight shipping. The approximate distance between Shanghai and Rotterdam via the Suez Canal is 19 000 km (<http://sea-distances.org/Sea-distances.org>, 2019) and was applied in this study. In PCD tip production, synthetic diamond powder (<2 µm in size) is used (see Section 3.2.2). However, the size of diamond grit industrially produced via HPHT is > 100 µm (Varnin et al., 2006) (see Section 3.1), why crushing is applied when conventional diamond powders are required (Zhang and Zou, 2017). Boudou et al. (2009) applied a jet mill in order to convert HPHT diamond grit, 150–190 µm in size, into smaller particles and reported that the majority (97%) of the milled powder had a size of <2 µm. Thus, a 97% yield of diamond powder with a size of <2 µm was assumed for the crushing process. In jet mills, feed particles are accelerated by a gas and reduced in size by collisions and the mill is always operated in a closed circuit (Bernotat and Schöner, 2000). The specific energy consumption of jet mills varies between 300 and 3000 kWh/metric ton (Bernotat and Schöner, 2000). This general value for jet mill energy consumption was assumed to also represent the size reduction of HPHT diamond grit into diamond powder <2 µm, specifically, and the midpoint value of 1650 kWh/metric ton was applied in this study, while the range was tested in the sensitivity analysis.

3.2.2. Polycrystalline diamond (PCD) tip production

The PCD tip production was based on data provided by the collaborators. Note that in certain cases, the exact materials used cannot be disclosed due to confidentiality. The PCD tip production includes three processes: HPHT sintering, disc processing and electrical discharge machining (Fig. 2). In the HPHT sintering of four PCD tips, 0.86 g diamond powder (<2 µm), 0.058 g cobalt powder and 9.0 g cemented carbide with 13 weight-% cobalt (WC-13Co) become sintered together in a high-pressure apparatus. A number of apparatus parts, including 9.2 g ceramic insulation materials, 5.9 g capsule components, 3.2 g other apparatus parts and 2.2 g pressure medium need to be replaced per four PCD tips. The discarded ceramic insulation materials and pressure medium become solid waste while the capsule components and other apparatus parts become recycled (8.0 g) or solid waste (1.1 g). The high-pressure apparatus WC-Co dies and anvils also need to be replaced, although less often: 7.1 g WC-Co are required per four PCD tips, and these become recycled. The resulting sintered disc, containing PCD on a WC-13Co substrate, is then grinded and polished until it has obtained a desired shape. A diamond powder slurry, which is being reused within the process, is applied for the grinding and polishing. The amounts of 0.24 g PCD and 4.9 g WC-13Co, which are worn away per four PCD tips in this process, become solid waste and recycled, respectively. The processed disc is then cut into a number of tips of the desired dimension (see Fig. 1) via electrical discharge machining, where another 0.14 g PCD and 1.2 g WC-13Co are worn away and become solid waste and recycled, respectively. In total, the production of four PCD tips, weighing 3.5 g, requires 10 kWh electricity. The production of the PCD tips takes place in Western Europe, why the WC-Co required was assumed to be produced outside China (Furberg et al., 2019b). Discarded WC-Co was assumed to be sorted and then recycled according to the scenarios described in Table 1.

3.2.3. Cemented carbide (WC-Co) tip production

With knowledge about the dimension of the WC-8Co tips (see Fig. 1) and the densities of tungsten carbide and cobalt, the weight of four WC-8Co tips could be calculated to 4.7 g. Inventory data per

kg of non-Chinese WC-8Co was then applied (Furberg et al., 2019b) considering the anticipated use within Europe.

3.2.4. Assembly

The assembly of tips on a tool body can be conducted in various ways but according to the collaborators, tips are typically brazed, fastened or screwed onto the substrate. When inserts are brazed to the tool body, the tool body is discarded with the inserts after use. When inserts are not brazed but screwed onto the substrate, then the substrate can be reused a number of times before it is discarded. Whether the tips are brazed or screwed onto the tool body depends on the tool makers preferences. In wood working, it is more common with brazing, e.g. due to the specific structures that are shaped in the wood product. In titanium alloys machining, it is more common with tips screwed onto the tool body. The process of assembly as well as the tool bodies was excluded from this study since the collaborators report that the assembly process and the tool body handling will not differ considerably between the PCD and WC-Co tool when used in the same applications.

3.2.5. Use phase

Most of the energy use in machining is consumed outside of the machining process itself and is related to, for example, the pumping of coolants (Gutowski et al., 2005; Vijayaraghavan and Dornfeld, 2010). For example, cutting fluids are required by most abrasive processes and the provision and cleaning of these fluids requires high amounts of energy (Aurich et al., 2013). Gutowski et al. (2005) show that about 32% or more of the energy use in machining can be related to the cutting fluids, applying the automotive industry as an example, while the machining process itself represent only about 15%. Based on the indications that i) both WC-Co and PCD tools use cutting fluids, where the maintenance of the cutting fluids is responsible for the larger part of the energy consumption, and ii) the cutting energy is responsible for a smaller part of the total energy use in machining, the use phase was assumed to be similar for the WC-Co and PCD tools in this study. The collaborators state that discarded WC-Co tips and the WC-Co substrates in the PCD tips are sent off to recycling, while the diamond burns off.

4. Results and discussion

4.1. Synthetic diamond grit production

Life cycle impact assessment (LCIA) results for HPHT production of synthetic diamond grit (0.1–1 mm in size) for the impact categories of CED [MJ eq], climate change [kg CO₂ eq], mineral resource scarcity [kg Cu eq] and abiotic depletion [kg Sb eq] are presented in Fig. 3. A summary of the results for all the included impact categories in this study are provided in Section S4.1 in the SM.

The main contributor to all impact categories in the HPHT synthesis of synthetic diamond grit is the production of Chinese WC-8Co present in the high-pressure apparatus. For the total CED, the main contribution in all scenarios is from the use of fossil resources in Chinese WC-8Co production (71–83% of the total CED). Climate change is also dominated by the Chinese WC-8Co production (81–97%) in all scenarios. The impact category of mineral resource scarcity is dominated by the use of tungsten resources in Chinese WC-8Co production in the current and solar scenario (94%), while the use of tungsten resources in Chinese WC-8Co production (57–58%) and market for nickel (42%) both contribute notably in the full recycling and solar-full recycling scenarios. The largest contributor to abiotic depletion is the use of tungsten resources in Chinese WC-8Co production for all scenarios with 96–100%. Recycling of WC-Co, which is 95% in the full recycling and solar-full recycling scenarios, greatly reduces the environmental and

resource impacts of HPHT synthesis with 56–91% for all impact categories in Fig. 3. Note that because all impacts are clearly dominated by the Chinese WC-8Co production, which is a part of the background system, changes made in the solar and solar-full recycling scenarios regarding the type of direct electricity input to the foreground system process of HPHT do not alter the results to a larger extent.

4.2. Comparison between polycrystalline diamond and cemented carbide tools

LCIA results for the comparison of PCD and WC-Co tools in titanium alloys machining and wood working are presented in Fig. 4 for the impact categories CED [MJ eq], climate change [kg CO₂ eq], mineral resource scarcity [kg Cu eq] and abiotic depletion [kg Sb eq]. A summary of the results for the PCD tool and the WC-Co tool for all included impact categories in this study are presented in Section S4.2 in the SM.

For the PCD tool, the main contribution to the CED in the current and full recycling scenarios is from the market for electricity, required in PCD production, based on fossil resources (39–43%). In the solar and solar-full recycling scenarios, the production of the photovoltaic electricity for PCD production, in turn using solar, wind and geothermal resources, constitutes the largest contributor to CED with 57–66%. The largest contributor to climate change is the market for the electricity required in PCD production in the current and full recycling scenarios with 78–88%. In the solar and solar-full recycling scenarios, it is the production of photovoltaic electricity required in PCD production that contribute the most to climate change with 38–57%. The largest contributor to mineral resource scarcity is the market for molybdenum with 31–78% in all scenarios. For abiotic depletion, the largest contributor is primary Chinese WC-8Co production (41–42% of abiotic depletion), mainly due to the use of tungsten resources, in the current and solar scenarios. The market for molybdenum is the main contributor to abiotic depletion in the full recycling and solar-full recycling scenarios with 23–28%. It should be noted that the results for the PCD tool do not include re-sharpening, which is common in wood working and can be done up to nine times according to the collaborators.

For the WC-Co tool, the main contribution to CED comes from the market for electricity from nuclear resources in primary non-Chinese WC-8Co production in the current scenario (17% of CED) and the market for electricity from nuclear resources in recycled non-Chinese WC-8Co production in the full recycling scenario (40% of CED). In the solar scenario, photovoltaic electricity production from wind, solar and geothermal resources in primary non-Chinese WC-8Co production contributes the most to the CED with 19%. While it is the photovoltaic electricity production from wind, solar and geothermal resources in recycled non-Chinese WC-8Co production that contribute the most to CED in the solar-full recycling scenario with 56%. The largest contributor to climate change in the current scenario is the market for electricity (24%) in primary non-Chinese WC-8Co production. The production of tannin required in primary non-Chinese WC-8Co production contribute the most to climate change in the solar scenario with 28%. In the full recycling and solar-full recycling scenarios, it is the market for electricity in recycled non-Chinese WC-8Co production that contribute the most to climate change (50–77%). Regarding mineral resource scarcity and abiotic depletion, the use of tungsten resources in primary non-Chinese WC-8Co production is the main contributor in all scenarios with 91–93% and 89–98%, respectively.

The scenario analysis shows that WC-Co recycling greatly reduce environmental and resource impacts for the WC-Co tool. The full recycling scenario illustrates a 55–65% reduction in CED

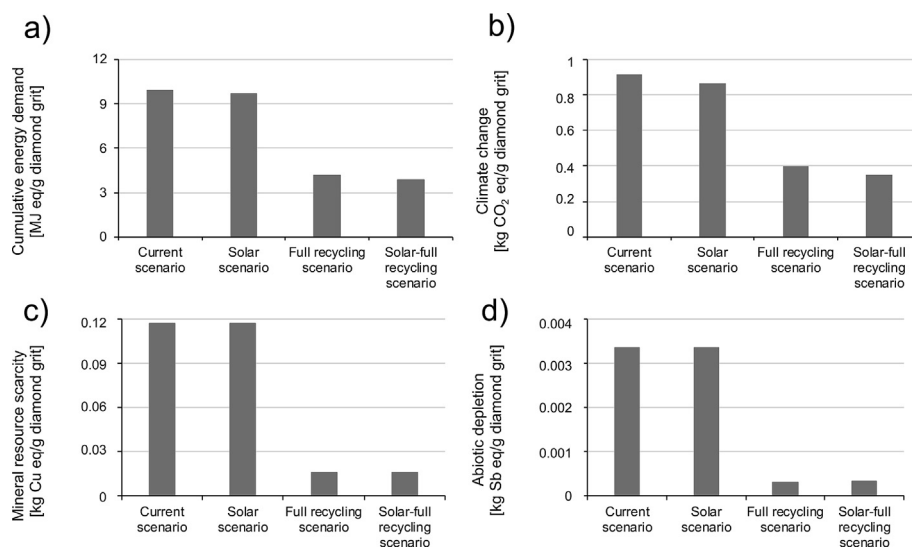


Fig. 3. Life cycle impact assessment results for high-pressure high-temperature (HPHT) synthesis of 1 g synthetic diamond grit (0.1–1 mm in size) for a) cumulative energy demand CED [MJ eq], b) climate change [kg CO₂ eq] c) mineral resource scarcity [kg Cu eq] and d) abiotic depletion [kg Sb eq] for the current, solar, full recycling and solar-full recycling scenarios.

and climate change and a 91–92% reduction in mineral resource scarcity and abiotic depletion for the WC-Co tool compared to the current scenario. Furthermore, the use of solar direct electricity inputs to the foreground processes instead of location-specific electricity for the PCD tool reduces the CED and climate change with 46–65% compared to the current scenario. In the solar-full recycling scenario, the CED as well as the climate change are reduced by 53–77% and 76–87% for the PCD and WC-Co tool, respectively, while the mineral resource scarcity as well as the abiotic depletion are reduced by 59–83% and 91% for the PCD and WC-Co tool, respectively.

The comparison between PCD and WC-Co tools for wood working shows that the PCD tool clearly performs better for all impact categories and scenarios presented in Fig. 4 except for CED and climate change in the full recycling and solar-full recycling scenarios. The results for freshwater eutrophication and terrestrial acidification are similar; the PCD tool performs better for freshwater eutrophication except in the full recycling and solar-full recycling scenarios, while PCD performs better for terrestrial acidification in all scenarios except the full recycling scenario. This is because the impacts in primary WC-Co production are much reduced when full recycling of WC-Co is applied. The comparison between PCD and WC-Co tools for titanium alloys machining shows that it is the WC-Co tool that performs better from an environmental perspective. It is less clear whether the PCD tool or the WC-Co tool performs better from a resource perspective in this application, since the results for the mineral resource scarcity and abiotic depletion indicators disagree. For mineral resource scarcity, the WC-Co tool performs better (Fig. 4 c) while the results for abiotic depletion shows that the PCD tool has lower resource impacts in the current and solar scenarios but higher impacts in the full recycling and solar-full recycling scenarios (Fig. 4 d). These contradicting results for mineral resource scarcity and abiotic depletion in the current and solar recycling scenarios stem from that these indicators put emphasis on different resources. This is clearly shown by the different main contributors identified for mineral resource scarcity and abiotic depletion in the current and solar scenarios for the PCD tool (see Table S13 in the SM). Note that while the comparison of the PCD and WC-Co tools in wood working represents real use, the comparison of PCD and WC-Co tools in

titanium alloys machining does not reflect real use but a conservative estimate made by the collaborators. Furthermore, there are uncertainties related to the assumption on similarity in the use phase between the two tools. This assumption was made due to limited data in this study and should be verified in future studies of hard material tools.

4.3. Sensitivity analysis results

The results from the sensitivity analysis conducted for HPHT synthesis show that one parameter for which realistic ranges were available in literature caused variations in the LCIA results with more than 10% relative to their baseline values in the current scenario: the reaction time in the high-pressure apparatus. The high value applied in the sensitivity analysis (30 min vs a baseline of 10 min) caused a 12% and 10% increase for climate change and CED, respectively. In addition, a number of parameters for which realistic ranges were unavailable also caused variations in the LCIA results with more than 10% relative to baseline values in the current scenario. These parameters included: (1) the amount of metal solvent per amount graphite and (2) the graphite-to-diamond conversion, which caused changes with more than 10% in terrestrial acidification and freshwater eutrophication, as well as (3) the weight of a conventional cubic apparatus WC-Co anvil, (4) the output from the reaction (one cycle), (5) the lifetime of WC-Co anvils and (6) the yield of purified diamonds which caused changes with more than 10% to all the impact categories included in this study. Several of these identified parameters relate to the amount of WC-Co needed for the HPHT synthesis, which is not surprising since WC-Co represented the main hotspot for HPHT synthesis.

The results from the sensitivity analysis for industrial PCD production identify the same parameters as in the hotspot analysis in Section 4.2, e.g. the electricity input to PCD production and the WC-Co input to HPHT sintering, to cause changes in the LCIA results above 10% relative to baseline values in the current scenario. In addition, the yield when crushing diamond grit (going from >100 µm to <2 µm) and the diamond powder input to the HPHT sintering also caused >10% changes.

Note that for some parameters, a ±50% variation relative to their baseline values might not be realistic. Still, we recommend that the

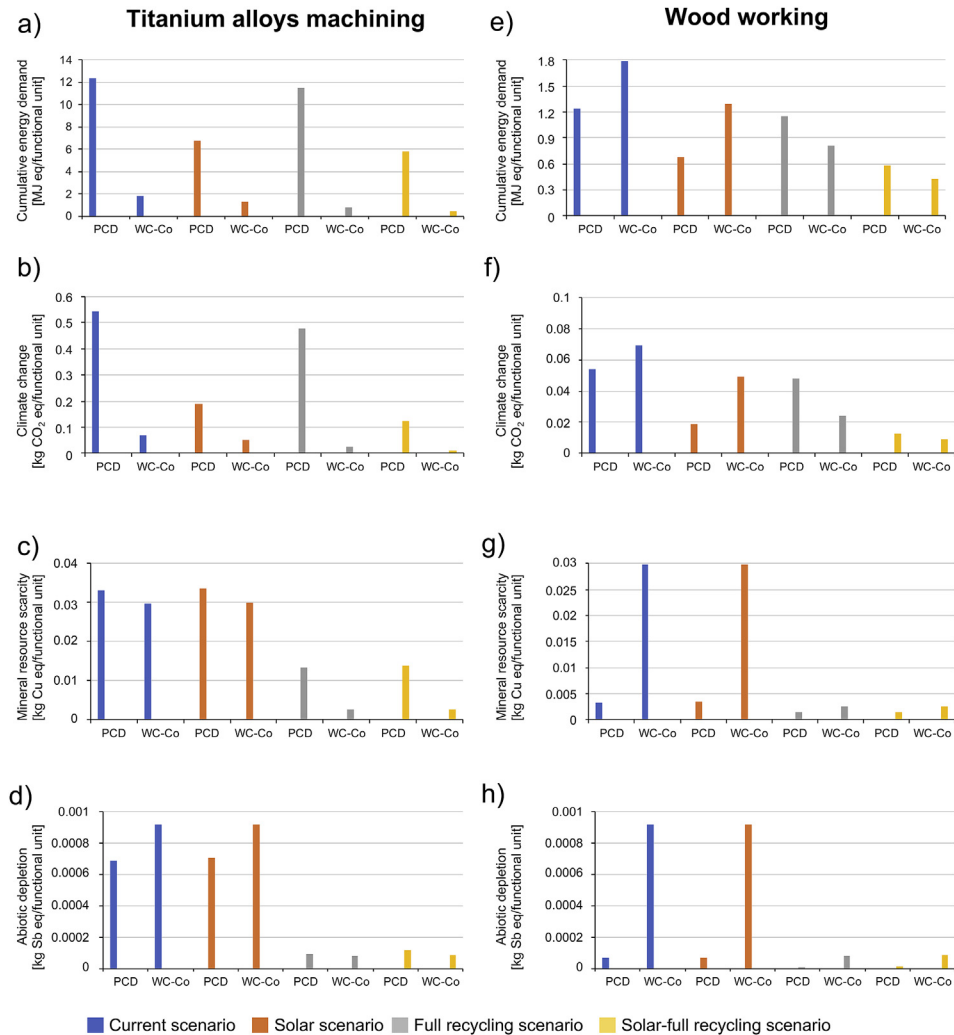


Fig. 4. Life cycle impact assessment results for the comparison of polycrystalline diamond (PCD) and cemented carbide (WC-Co) tools in titanium alloys machining and wood working per functional unit, including a) cumulative energy demand CED [MJ eq], titanium alloys machining, b) climate change [kg CO₂ eq], titanium alloys machining, c) mineral resource scarcity [kg Cu eq], titanium alloys machining, d) abiotic depletion [kg Sb eq], titanium alloys machining, e) cumulative energy demand CED [MJ eq], wood working, f) climate change [kg CO₂ eq], wood working, g) mineral resource scarcity [kg Cu eq], wood working and h) abiotic depletion [kg Sb eq], wood working, for the current, solar, full recycling and solar-full recycling scenarios. The functional unit in the case of titanium alloys machining is the surface area generated by one WC-Co tool during its lifetime, while the functional unit in wood working is the mass of wood removed by one WC-Co tool during its lifetime.

Table 2

Break-even analysis of the polycrystalline diamond (PCD) versus cemented carbide (WC-Co) tool performance for the current, solar, full recycling and solar-full recycling scenarios. Values in the table were obtained by dividing the impact of one PCD tool with the impact of one WC-Co tool, i.e. the values in this table are not dependent on specific applications but correspond to environmental and resource targets to be reached in order for the PCD tool to perform better than the WC-Co tool.

Impact category	Current scenario	Solar scenario	Full recycling scenario	Solar-full recycling scenario
Climate change [kg CO ₂ eq]	78	38	200	140
Terrestrial acidification [kg SO ₂ eq]	23	12	150	79
Freshwater eutrophication [kg P eq]	63	44	570	380
Cumulative energy demand [MJ eq]	69	52	140	140
Mineral resource scarcity [kg Cu eq]	11	11	53	54
Abiotic depletion potential [kg Sb eq]	7.5	7.7	11	14

parameters identified as sensitive should receive additional attention in further investigations, e.g. in terms of obtaining realistic ranges for these parameters.

4.4. Break-even analysis results

The results from the break-even analysis are presented in Table 2 and illustrates the required performance difference

between PCD and WC-Co tools in order for one PCD tool to be preferable from an environmental or resource perspective compared to the WC-Co tool. The results show that the PCD tool constitutes an environmental and resource preferable alternative compared to WC-Co tools for all the impact categories included in this study if its performance is more than 78 and 52 times the performance of a WC-Co tool in the current and solar scenario, respectively. In the full recycling and solar-full recycling scenarios,

the performance of the PCD tool need to be more than 570 and 380 times the performance of a WC-Co tool, respectively, if it should constitute a preferable alternative compared to WC-Co for all included impact categories. This is since the impacts of the WC-Co tool is reduced to a larger extent than the impacts of the PCD tool when a higher recycling rate of WC-Co is applied. Furthermore, Table 2 clearly indicate a trade-off between environmental and resource impacts. This is since the environmental impact categories, compared to the resource impact categories, require a much higher performance difference between the PCD and WC-Co tool for the former to be preferable.

5. Conclusions

This study provides the first LCA of industrial PCD production, which was based on data from a global leader in the development and production of synthetic diamond. Furthermore, this study provides the first LCA of PCD's precursor synthetic diamond grit, as well as the first comparative LCA on PCD and WC-Co tools. The provided LCI data for diamond grit and PCD production can be used as input to future LCAs of other synthetic diamond or PCD products, thus enabling further comparisons to conventional materials in different applications.

A number of recommendations on how synthetic diamond and tool manufacturers can improve the environmental and resource performances of their processes can be derived from the LCIA results of this study. Synthetic diamond manufacturers are recommended to increase the recycling rate of WC-Co, which is used in the high-pressure apparatus, since this greatly reduces the environmental and resource impacts of the HPHT synthesis. PCD tool manufacturers are recommended to apply renewable energy sources for the direct electricity input to their processes, since the environmental impacts of the PCD tool are greatly reduced when solar electricity instead of current location-specific electricity is used. In the WC-Co tool production, the use of electricity and tungsten resources constitute main contributors to environmental and resource impacts. Therefore, WC-Co tool manufacturers are recommended to recycle WC-Co, which greatly reduces both environmental and resource impacts.

Regarding the comparison of PCD and WC-Co tools, this study shows that the higher performance of PCD can make it preferable from an environmental and resource perspective in certain applications. The potential to reduce environmental and resource impacts by substituting WC-Co with PCD in the application of wood working was shown for all included impact categories in the current and solar scenarios. This was also the case in the full recycling and solar-full recycling scenarios for mineral resource scarcity and abiotic depletion. However, it was not the case for climate change, terrestrial acidification, freshwater eutrophication and CED in the full recycling scenario, nor for climate change, freshwater eutrophication and CED in the solar-full recycling scenario. This is since the impacts of the WC-Co tool are largely reduced in the corner-stone scenarios representing full recycling of WC-Co. The use of the PCD tool in titanium alloys machining, on the other hand, did not show a potential for reduced environmental and resource impacts compared with the WC-Co tool. The results from this study show that a life-cycle perspective is important for identifying trade-offs between environmental and resource impacts in the comparison of PCD and WC-Co tools, since the PCD tool is less dependent on tungsten but on the other hand requires larger amounts of electricity for its production processes.

CRedit authorship contribution statement

Anna Furberg: Conceptualization, Methodology, Investigation,

Formal analysis, Visualization, Project administration, Writing - original draft, Writing - review & editing. **Kristin Fransson:** Investigation, Writing - review & editing. **Mats Zackrisson:** Investigation, Writing - review & editing. **Mikael Larsson:** Investigation, Writing - review & editing. **Rickard Arvidsson:** Conceptualization, Methodology, Visualization, Supervision, Funding acquisition, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.123577>.

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